I-5 Ship Canal Bridge: Noise Pilot Project
Measurement Results

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RESULTS AT A GLANCE

What did the I-5 Ship Canal Bridge pilot noise abatement study find?

From 2010 - 2011, the Washington State Department of Transportation measured noise level reductions from the vertically hung noise-absorptive panels at the south concrete approach above the express lanes on the I-5 Ship Canal Bridge in Seattle. This project is the first time that this type of material has been used in this type of application. The report summarizes the results I-5 Ship Canal Bridge Pilot Noise Study (noise pilot project) after one year of monitoring.

Modeling of the vertically hung absorptive panels predicted 4 to 5 decibels (dB) of noise reduction were possible (HDR, 2009). The average human ear notices noise reductions as small as 3 dB; 10 dB reductions sound half as loud.

The first year results are as follows:

- The panels provided 0-4 dB of noise reduction to nearby residents along the south concrete approach of the bridge.
- Despite measured noise reductions with the panels, an Analysis of Variance (ANOVA) statistical test indicates that post-construction measurements are not significantly quieter than pre-construction noise measurements.
- An ANOVA statistical test of the four quarters of post-construction noise measurements indicates that there are no significant seasonal differences in the noise levels or traffic counts.

What constraints were there on the project?

The unique nature of the bridge created numerous challenges for designing noise reduction. Constraints included the following:

- Aesthetics; views of and from the bridge
- Maintaining structural integrity; wind and dead loading
- Access; bridge inspections, bird and rodent habitat
- Maintenance; graffiti cleanup, durability of materials

Why did the test panels not perform as predicted?

- The noise models underestimated the total noise in the project area because they couldn't account for diffracted or direct path noise and only analyzed reflected noise and the absorptive panels.
- Noise is diffracting around or reflecting off of the hard edges of the test panels which could reduce their effectiveness. The panels also have steel corners for reinforcement which could be reflecting or diffracting noise.
- Noise is reflected out from the exposed ceiling between the panels and directly over express lane traffic. The locations closest to the bridge (e.g. Sites 10 and 18) which received the lowest reductions have a direct line-of-sight to the ceiling. Receivers farther away (e.g. Site 15) have higher reductions because the panels block more of the view to the ceiling.

What happens next?

WSDOT committed to monitoring the project for three years total. Monitoring commitments in year two and year three included the following:

- Collect annual noise measurements at locations around the project area and evaluate panel durability and maintenance issues.
- Consider input from affected residents and businesses.
- Evaluate whether additional analysis techniques can help WSDOT better understand how the noise panels are performing.
- Brief elected officials and representatives, the Washington State Transportation Commission and others at WSDOT.

The results from the first year of testing do not suggest that any changes in performance should be expected in year two or year three. The acoustic performance has been consistent throughout the first year during quarterly measurements and there is no evidence of physical deterioration of the materials. Therefore, WSDOT proposes to end regular evaluations of the Noise Pilot Project after one year and for this report to be considered the final summary report.

INTRODUCTION

Background

WSDOT has worked with the Eastlake community for almost 20 years to identify and implement methods for reducing traffic noise levels coming from I-5, as funding has allowed. This document summarizes the noise-reduction methods and studies WSDOT has pursued, and provides references to more detailed materials. The dominant source of noise for residents north of E. Hamlin Street is from traffic on the I-5 express lanes. Communities around the Ship Canal Bridge asked WSDOT to reduce the traffic noise by closing the express lanes at night. In 1997, WSDOT was able to secure funding for operations of ongoing nightly closures of the I-5 express lanes.

Between 2003 and 2008, through the 2003 and 2005 gas tax, WSDOT secured funding to build noise walls on either side of I-5 near the south end of the Ship Canal Bridge.

Since 2004, WSDOT has explored additional options for reducing noise in the area. After extensive internal discussions, an Expert Review Panel (ERP) of four national acoustic experts was convened. Given the constraints on the project, the One of the ERP recommendations was to hang acoustically absorptive panels from the underside of the I-5 mainline, above the I-5 Express Lanes. This recommendation became the Noise Pilot Project described here.

In 2010, WSDOT installed approximately 700 noise-absorptive ceiling panels above the I-5 express lanes on the south end of the Ship Canal Bridge between E. Gwinn Place and E. Allison Street. The panels were hung vertically on the outer edges of the ceiling. They were designed to absorb and block the traffic noise that bounces off the ceiling of the express lanes and into the surrounding neighborhoods.

This is the first time this type of material has been used in this type of application. WSDOT agreed to monitor the test section to evaluate its effectiveness at reducing noise and its durability in this environment. This report outlines the noise measurements collected over the first year following construction and highlights other lessons learned.

What noise regulations are relevant?

In the 1970's the federal government established the following noise regulations and procedures to address transportation related noise:

- *Noise Control Act of 1972*. Traffic noise regulation requiring federal agencies to implement noise programs.

- *Procedures for Abatement of Highway Traffic Noise and Construction Noise* (23 CFR 772). Requires that the Federal Highway Administration (FHWA) do the following:
    - Issue specific highway traffic noise rules in 1976
    - Set up the federal aid program to include financial support for highway noise mitigation
    - Identify two types of noise mitigation projects: Type I: mandatory for new construction after 1976, and Type II: voluntary to address pre-existing conditions before 1976 (i.e., “retrofits”).

WSDOT established a Type II voluntary retrofit program that included a prioritization of eligible locations for noise abatement. WSDOT developed an agency directive (D22-22) in the late 1970’s (updated in 1987) that established criteria for equitably ranking the retrofit sites. We use a cost benefit calculation that includes:

- Noise level before project
- Noise level after project
- Number of sensitive “receivers” (noise sensitive properties like homes, churches, schools, etc.)
- Cost of noise reduction

WSDOT initially considered the Ship Canal Bridge for retrofit ranking in 1977. The bridge was removed from consideration at that time because acceptable lightweight materials were not available, analysis methods had not been developed, and the cost was thought to be too high.

In the 1990’s, residents requested that WSDOT close the I-5 express lanes to reduce noise at night. In 1997, WSDOT was able to secure funding for operations of ongoing nightly closures of the I-5 express lanes. WSDOT initially closed the express lanes from midnight to 4 a.m. In July of 2012, WSDOT completed the I-5 Express Lane Automation project that allows for extended express lanes closures on weeknights from 11 p.m. to 5 a.m. On weekends the express lanes do not open until 7 a.m.

Currently, 56 sites have been identified, including the Ship Canal Bridge. The Bridge was ranked number four when the Noise Pilot Project was originally funded.

What is the study area?

The study area is a 500 foot long section of the south concrete approach of the Ship Canal Bridge. It includes communities on both the east and west side of the concrete approach (Figure 1).

Bridge Traffic Noise

Due to the two level structure of the bridge, nearby residents hear high noise levels from two sources:

- "Direct path" noise comes from cars and trucks on the roadway directly to the listener.
- "Reflected path" noise that is reflected off the bottom of the mainline.

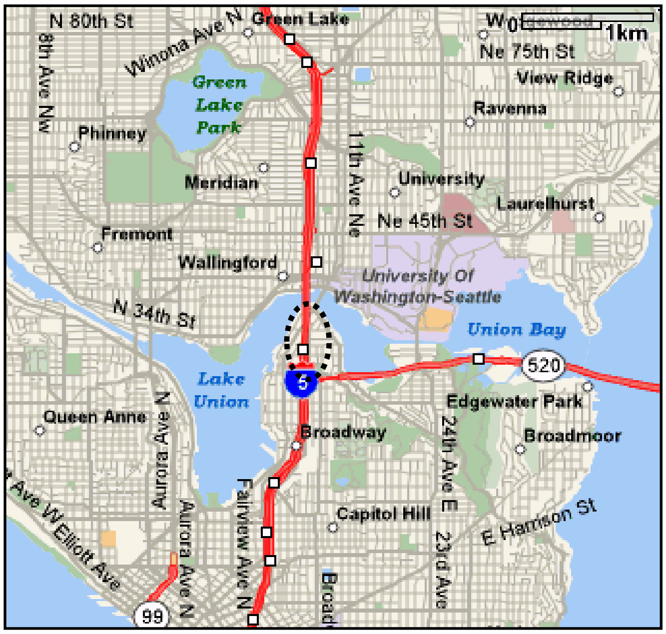


Figure 1: Ship Canal Bridge pilot study area

What makes this a Noise "Pilot" Project?

The Ship Canal Bridge is unique. It is a double-decker bridge carrying more than 200,000 vehicles per day that goes through a dense urban neighborhood with residences constructed very near the structure. Opened in 1962, the Ship Canal Bridge has been nominated for the National Historic Registry, and is locally and regionally iconic. Acoustically, the bridge creates a complex noise environment with both direct path and reflected path noise and other traffic sources (Figure 2).

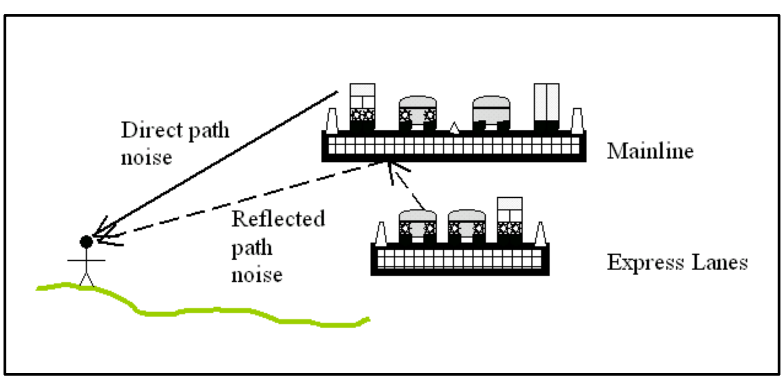


Figure 2: Direct Path and Reflected Path Sound

The unique nature of the bridge created numerous challenges for designing noise reduction. Constraints included the following:

- Aesthetics; views of and from the bridge
- Maintaining structural integrity; wind and dead loading
- Access; bridge inspections, bird and rodent habitat
- Maintenance; graffiti cleanup
- Durability; more than 25 years of expected life remaining
- Cost

Given the significant design challenges with the bridge, there was not an obvious cost-effective solution for reducing noise. Even after bringing in national acoustic experts, there remained uncertainty about the effectiveness of noise reduction options. The project was determined to be a research project, or Noise Pilot Project, to allow WSDOT to do the following:

- Evaluate the ceiling panels for durability, wind loads, installation, appearance and the effect on the bridge structure
- Determine if the selected ceiling panel materials would provide the predicted noise reductions
- Respond to neighborhood desires for reasonable options to reduce high noise levels
- Verify the noise modeling results with field measurements
- Apply what we learn on future similar projects.

What material was used for the pilot study?

WSDOT considered a variety of products with different levels of effectiveness and eventually selected a quilted absorptive panel with the trade name of Sound Seal, model BBC-EXT-2QT-UH Sound Baffles. The product was selected for its combination of acoustic features, durability, and ability for use in this application. The material selected is not currently approved by WSDOT.

The product had the following characteristics:

- Exterior grade vinyl coated polyester facing
- 1/2 –inch thick internal Ultra High Molecular Weight Polyethylene stiffener
- 2-inches of fiberglass batting
- One pound per square foot reinforced loaded vinyl noise barrier backing.

- Sound Absorption Coefficients (SAC) values of 0.74 at 500 Hz and 0.72 at 1000 Hz. So 74% and 72% of the energy are absorbed at these frequencies, respectively.

This study analyzed the following related to the absorptive product:

- Measured frequencies indicate that approximately 22% of the energy is being absorbed at 500 Hz and 27% at 800 Hz.

Measurement Results

Noise levels were monitored for two quarters prior to the installation of the absorptive noise panels and then quarterly for the first year at 18 locations on the ground and four stations on the bridge near the source.

Note: the average human ear notices noise reductions as small as 3 decibels; 10 decibel reductions sound half as loud to the human ear.

- Within the study area, noise levels were 0-4 dB lower after the panels were installed. Most of the reductions were not audible.
- Outside the study area, two locations measured 1- 2 dB higher after the panels were installed.
- There were no significant differences in pre-construction versus post-construction traffic volumes, based on traffic counts.
- Heavy truck counts were significantly lower in fall 2010 and summer 2011 than in the other measurement periods. However, results do not suggest a measurable effect.

Table 1: Average Noise Levels and Noise Reductions (difference) at Ship Canal Bridge Monitoring Locations

Location	Pre-Construction Average (dBA)	Post-Construction Average (dBA)	Difference (dBA)
A	92.3	91.8	- 1
B	-	91.2	-
C	91.0	91.8	+ 1
D	-	91.7	-
1	83.5	80.5	- 3
2	82.4	78.8	- 4
3	82.4	80.3	- 2
4	74.3	71.5	- 2
5	79.4	77.3	- 2
6	70.3	69.3	- 1
7	81.6	80.0	- 2
8	78.6	77.5	- 1
9	79.8	80.8	+ 1
10	82.6	82.0	- 1
11	79.8	82.0	+ 2
12	77.8	78.0	0
13	79.4	78.3	- 1
14	69.8	70.0	0
15	79.3	76.3	- 3
16	75.2	73.8	- 1
17	83.2	82.3	- 1
18	83.3	82.5	- 1

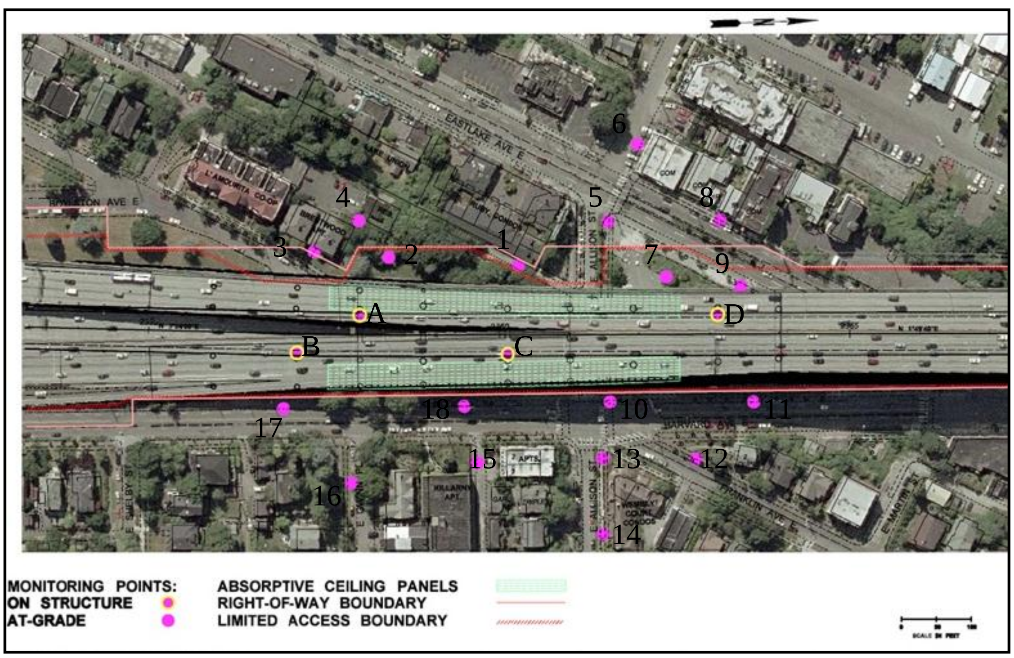


Figure 3: Ship Canal Bridge Noise Pilot Study Area

Why did the noise panels not work as predicted?

Results from two noise models were combined to predict noise reductions from the noise pilot project because no single proven model was capable of modeling direct path traffic noise, sound diffraction, and reflected noise. The original noise modeling used the Federal Highway Administration's (FHWA) Traffic Noise Model (TNM) to predict traffic noise levels and sound bending (diffracting) around objects. The Enhanced Acoustic Simulator for Engineers (EASE) model was used to predict reflected noise.

- The noise models underestimated the total noise in the project area because they couldn't account for diffracted or direct path noise and only analyzed reflected noise and the absorptive panels.
- Noise is diffracting around or reflecting off of the hard edges of the test panels which could reduce their effectiveness. The panels also have steel corners for reinforcement which could be reflecting or diffracting noise.
- Noise is reflected out from the exposed ceiling between the panels and directly over express lane traffic. The locations closest to the bridge (e.g. Sites 10 and 18) received the lowest reductions have a direct line-of-sight to the ceiling. Receivers further away (e.g. Site 15) have higher reductions because the panels block more of their view to the ceiling.

What are the recommendations?

At this time, WSDOT is uncertain about a path forward and no specific recommendations are proposed. WSDOT has worked with local and national experts to research solutions to build a pilot project that uses an innovative solution to fit within the many constraints of this historic bridge.

The agency has spent nearly 20 years and more than $7 million dollars, including direct funding and staff time, investigating the situation. Nearby noise reduction efforts, e.g., noise walls, along Harvard Avenue E and Boylston Ave E have exceeded $15 million dollars. At this point, it is difficult to say what else can be done with any amount of money.

NOISE BASICS

What causes traffic noise?

- Tires, exhaust pipes, and engines all make noise.
- Increases in traffic speed and traffic volume will increase traffic noise.
- Objects between you and the traffic may reduce the noise, such as hills, buildings and large masses of trees and shrubs.

What is a dBA?
dBA stands for A- weighted decibel. A weighted decibels measure sound at frequencies that people can hear.

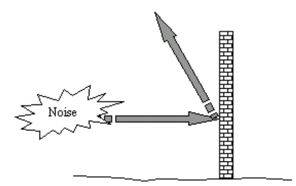
How do people hear sound?

People hear sound when their ears detect variations in the surrounding atmospheric pressure. When objects vibrate, they create pressure that reaches the ear as sound, called sound pressure.
The human ear can detect a range of pressure that is so large that it’s expressed on a logarithmic scale in units called decibels (dBA). The logarithmic scale compresses the large range of pressure into decibel units, which are easier to use.

People do not all perceive noise in the same way, but in general:

- Most people barely hear a three dBA change in sound.
- Most people readily hear a five dBA change in sound.
- For most people, a ten dBA change sounds like a doubling or halving of the sound level.

WSDOT evaluates noise reduction when traffic noise is at 66 dBA or higher. It is difficult to hold a conversation at this level of background noise.

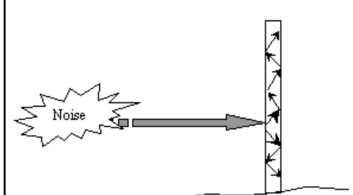


SOUND REFLECTION

How are humans affected by noise?

People can lose hearing if they are exposed to high levels of noise for long periods of time. Noise can also affect sleep, thought and conversation, and may aggravate some diseases.

- The Federal Highway Administration (FHWA) has established noise abatement criteria for traffic noise on highway projects based on the noise sensitive land uses surrounding the roadway.
- The State of Washington and local agencies establish noise limits for residential and other types of land uses. Motor vehicle use is exempt from these limits.



SOUND ABSORPTION

How do Noise Walls work?

Noise walls provide a barrier of solid material between the noise source and the person hearing the noise. The noise hits the barrier, blocking the noise. This is called sound reflection.

Other materials absorb sound. Sound pressure enters the absorptive material, containing open spaces in which the sound pressure loses energy. This is called sound absorption.

SHIP CANAL BRIDGE STUDIES

What studies have been done before?

- In 2003 WSDOT's SR 520 "Trans-Lake" project analyzed noise and structural issues.
- The WSDOT Bridge and Structures Office completed the *SR 5/520 Ship Canal Noise Mitigation Structural Feasibility and Cost Analysis*. The report identified limitations of several noise reduction methods, but also provided an opportunity to consider other methods of noise reduction needing additional research.
- Michael Minor and Associates completed the *Ship Canal Bridge Noise Abatement Feasibility Study Mitigation* in early 2004. Minor's report looked at several products and identified a variety of next steps to evaluate additional products and rank the bridge on the retrofit list.
- WSDOT completed supplemental noise report in late 2004 exploring innovative product solutions and additional complementary noise reduction systems.
- WSDOT received $5 million for further study from State Legislature.
- WSDOT convened an Expert Review Panel in 2008 who recommended a phased approach to abatement including vertical ceiling panels.
- WSDOT contracts with consultant to conduct reflective modeling of noise on bridge using EASE model.
- WSDOT constructed vertical noise panels in a test section on the concrete south approach of the bridge in 2010.

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APPENDIX A: NOISE BASICS

Characteristics of Noise

Sound

Sound is created when objects vibrate, resulting in a minute variation in surrounding atmospheric pressure. This is called *sound pressure*. The human response to sound depends on the magnitude of a sound as a function of its frequency and time pattern (EPA, 1974). Magnitude measures the physical sound energy in the air. The range of magnitude, from the faintest to the loudest sound that the ear can hear, is so large that sound pressure is expressed on a logarithmic scale in units called decibels (dB). Loudness, compared to physical sound measurement, refers to how people subjectively judge a sound and this varies from person to person. Noise is unwanted sound.

Sound Characteristics and Human Response

Humans respond to a sound's frequency or pitch. The human ear is very effective at perceiving sounds that have a frequency between approximately 1,000 and 5,000 Hz, and human hearing decreases outside this range. Environmental noise is composed of many frequencies, each occurring simultaneously at its own sound-pressure level. Frequency weighting, which is applied electronically by a sound level meter, combines the overall sound frequency into one sound level that simulates how an average person hears sounds. The commonly used frequency weighting for environmental noise is A-weighting (dBA), which is most similar to how humans perceive sounds of low to moderate magnitude.

How Humans Perceive Noise

Because of the logarithmic decibel scale, a doubling of the noise sources (e.g., the number of cars operating on a roadway) increases noise levels by three dBA. A ten-fold increase in the number of noise sources will add 10 dBA. As a result, a source that emits a sound level of 60 dBA, combined with another source of 60 dBA, yields a combined sound level of 63 dBA (not 120 dBA). The human ear can barely perceive a three dBA increase, but a five or six dBA increase is readily noticeable and sounds as if the noise is about one and one-half times as loud. To most listeners, a ten dBA increase appears to be a doubling in noise level.

Factors Affecting Traffic Noise

Noise levels from traffic sources depend on volume, speed, and the type of vehicle. Generally, an increase in volume, speed, or vehicle size increases traffic noise levels. Vehicular noise is a combination of sounds from the engine, exhaust, and tires. Other conditions affecting traffic noise include defective mufflers, steep grades, terrain, vegetation, distance from the roadway, and shielding by barriers and buildings.

Environmental Effects on Noise

Noise levels decrease with distance from the source. For a line source such as a roadway, noise levels decrease 3 dBA over hard ground (concrete, pavement) or 4.5 dBA over soft ground (grass) for every doubling of distance between the source and the receptor. For a point source such as construction, noise levels decrease between 6 dBA and 7.5 dBA for every doubling of distance from the source.

The type of terrain and the elevation of the receiver relative to the noise source can greatly affect the propagation of noise. Level ground is the simplest scenario: sound travels in a straight line-of-sight path between the source and receiver (Figure 4).

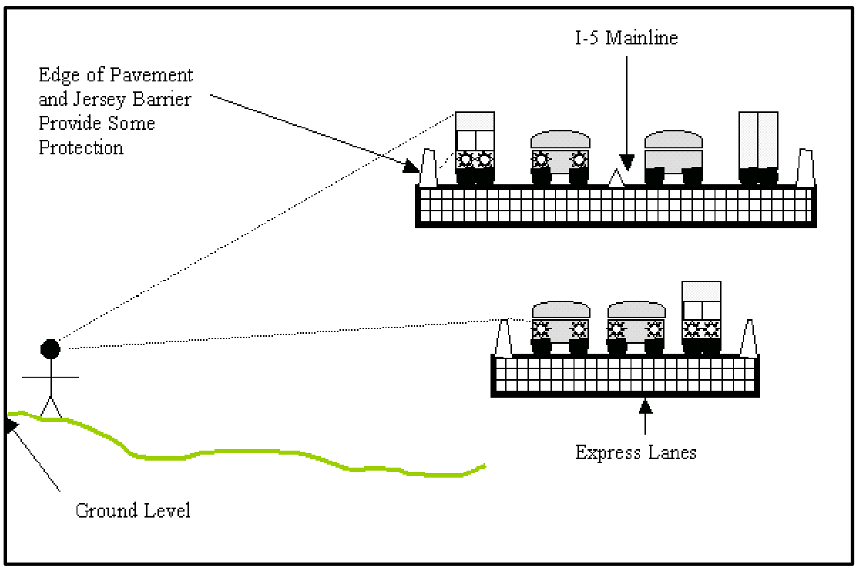


Figure 4: Elevated noise source

If the source is depressed or the receiver is elevated, noise generally travels directly to the receiver. Noise levels may be reduced in cases where the terrain crests between the source and receiver, resulting in a partial noise barrier near the receiver. If the source is elevated or the receiver is depressed, sound often is reduced at the receiver. The edge of the roadway can act as a partial noise barrier, blocking some sound transmission between the source and receiver (Figure 4). Even a short barrier (e.g., a solid concrete Jersey-type safety barrier) can reduce noise levels. Breaking the line of sight between the receiver and the noise source often results in a noise reduction of approximately five dBA.

Atmospheric Conditions

Atmospheric conditions such as wind, temperature, humidity, and precipitation, are not normally a major factor in most traffic noise analysis projects. However, in the present study the bridge structure is elevated above the community. Therefore, prevailing winds from the northwest during the winter months and the southwest during the summer months tend to carry more of the traffic noise farther east of the bridge and bend the sound waves towards the ground on the east side

Sound Level Descriptors

A widely used descriptor for environmental noise is the equivalent sound level (L_{eq}). The L_{eq} can be considered a measure of the average sound level during a specified period of time. It is a measure of total noise, or a summation of all sounds during a time period. It places more emphasis on occasional high noise levels that accompany general background sound levels. L_{eq} is defined as the constant level that, over a given period of time, transmits to the receiver the same amount of acoustical energy as the actual time-varying sound. For example, two sounds, one containing twice as much energy but lasting only half as long, have the same L_{eq} noise levels. L_{eq} measured over a one-hour period is the hourly L_{eq} [L_{eq}(h)] this is used for highway noise impact and abatement analyses.

Short-term noise levels (e.g., a single truck passing by) are described by either the total noise energy or the highest instantaneous noise level occurring during the event. The sound exposure level (SEL) is a measure of total sound energy from an event, and is useful in determining what the L_{eq} will be over a period in time when several noise events occur. The maximum sound level (L_{max}) is the greatest short-duration sound level that occurs during a single event. L_{max} is related to impacts on speech interference and sleep disruption. In comparison, L_{min} is the minimum sound level during a period of time.

People will generally find a moderately high, constant sound level more tolerable than a quiet background level interrupted by frequent high-level noise intrusions. An individual's response to sound depends greatly upon the range that the sound varies in a given environment. For example, steady traffic noise from a highway is normally less bothersome than occasional aircraft flyovers in a relatively quiet area. In light of this subjective response, it is often useful to look at a statistical distribution of sound levels over a given time period in addition to the average sound level. Such distributions identify the sound level exceeded and the percentage of time it is exceeded. Therefore, it allows for a more thorough description of the range of sound levels during a given measurement period. These distributions are identified with an L_n, where *n* is the percentage of time that the levels are exceeded. For example, the L_{10} level is the sound level that is exceeded 10 percent of the time.

Effects of Noise

Environmental noise at high intensities directly affects human health by causing hearing loss. Prolonged exposure to very high levels of environmental noise can cause hearing loss. The EPA has established a protective level of 70 dBA L_{eq}, below which hearing is conserved for exposure over a 40-year period (U.S. EPA, 1974). Although scientific evidence is not currently conclusive, noise is suspected of causing or aggravating other diseases. Environmental noise indirectly affects human welfare by interfering with sleep, thought, and conversation. The FHWA noise abatement criteria are based on speech interference, which is a well documented impact that is relatively reproducible in human response studies.

Noise Regulations and Impact Criteria

Applicable noise regulations and guidelines provide a basis for evaluating potential noise impacts. For Type I state and federally funded highway projects, traffic noise impacts occur when predicted LA_{eq} (h) sound levels approach or exceed the noise abatement criteria (NAC) established by the FHWA, or substantially exceed existing sound levels (U.S. Department of Transportation, 1973, Noise Abatement Council). The term "substantially exceed" is defined by WSDOT as an increase of 10 dBA or more to be a substantial increase.

Table 2: FHWA Noise Abatement Criteria

Activity Category	L_{eq} (h) (dBA)	Description of Activity Category
A	57 (exterior)	Lands on which serenity and quiet are of extraordinary significance and serve an important public need, and where preserving these qualities is essential if the area is to continue to serve its intended purpose.
B	67 (exterior)	Picnic areas, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals.
C	72 (exterior)	Developed lands, properties, or activities not included in Categories A or B above.
D	-	Undeveloped lands.
E	52 (interior)	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, and auditoriums.

Source: U.S. Department of Transportation, 1982.

The FHWA noise abatement criteria specify exterior LA_{eq}(h) noise levels for various land activity categories (Table 2). For receptors where serenity and quiet are of extraordinary significance, the noise criterion is 57 dBA. For residences, parks, schools, churches, and similar areas, the noise criterion is 67 dBA. For developed lands, the noise criterion is 72 dBA. WSDOT considers a noise impact to occur if predicted $LA_{eq}(h)$ noise levels approach within one dBA of the noise abatement criteria in Table 2. Thus, if a noise level were 66 dBA or higher, it will approach or exceed the FHWA noise abatement criterion of 67 dBA for residences.

Land use in the study area includes residential, parks, commercial, industrial, schools and some undeveloped uses (see Figure 1 for map showing quadrants). In the southwest quadrant of the study area land use is primarily residential in the south, changing to a mix of residential, commercial, and industrial uses farther north. There are several apartments under the bridge at Eastlake Avenue E. and E. Allison and several houseboats located along the waterfront.
The Southeast quadrant of the study area is almost exclusively residential. There are some residences that have been converted to commercial use near Franklin Avenue East. North of Franklin to Eastlake Avenue East land use is mixed with residential and commercial uses. North of Eastlake Avenue E. land use is commercial with several residential uses including houseboats under the bridge.
In the northwest quadrant land use is primarily residential near I-5. John Stanford International School is located near the bridge along 5th Avenue NE. Farther south, land use changes to primarily commercial and industrial, and parklands and trails along most of the waterfront. In the northeast quadrant land use is primarily residential near I-5 and changes to commercial and industrial down to the waterfront.

The City of Seattle property line noise regulations are outlined in SMC 25.08.410 of the municipal code. The maximum permissible noise levels depend on the land uses of both the source noise and receiving property (Table 3). The environmental designation for noise abatement (EDNA) is defined by the land use of a property. In general, residential uses are class A, commercial are class B, and industrial are class C.

Table 3: Maximum Permissible Environmental Noise Levels

EDNA OF NOISE SOURCE	EDNA OF RECEIVING PROPERTY		
	Residential (dBA)	Commercial (dBA)	Industrial (dBA)
Rural	52	55	57
Residential	55	57	60
Commercial	57	60	65
Industrial	60	65	70

Source: Seattle Municipal Code SMC 25.08.410

Noise from traffic operating on public roadways is exempt from SMC 25.08.410. Construction noise is exempt from property line standards during daytime hours. Nighttime construction noise from the project, however, must meet 10 dB below City of Seattle property line regulations (Table3) between 10 p.m. and 7 a.m.

Construction Noise

Construction of any of the noise walls requires nighttime construction activities. Therefore, a nighttime noise variance is required from the City of Seattle. Construction noise mitigation requirements will be developed in coordination with the City and specified in the noise variance. To reduce construction noise at nearby receptors, mitigation measures such as the following could be incorporated into construction plans, contractor specifications, and variance requirements:

- Develop a construction monitoring and management plan that establishes specified noise levels that may not be exceeded by the contractor during specific time periods.
- Construct temporary noise barriers or curtains around stationary equipment and long-term work areas located close to residences.
- Limit the noisiest construction activities to before 10:00 PM on weekdays and weekends reducing construction noise levels during sensitive nighttime hours.
- Equip construction equipment engines with adequate mufflers, intake silencers and engine enclosures.
- Use the quietest equipment available.
- Require the use of OSHA approved ambient sound level backup alarms.
- Turn off construction equipment during prolonged periods of non-use.
- Maintain all equipment and train operators in their proper use.
- Where possible, locate stationary equipment away from sensitive receiving properties
- Provide a 24-hour noise complaint line.
- Notify nearby residents prior to periods of intense nighttime construction

APPENDIX B: RESULTS

Characteristics of Noise

Table 4: Pre- and post-construction noise measurements for the Ship Canal Bridge pilot noise study.

		Pre-Construction			Post-Construction				
Location	Location Description	December 2009 (dBA)	February 2010 (dBA)	Average Pre-Con (dBA)	October 2010 (dBA)	February 2011 (dBA)	July 2011 (dBA)	September 2011 (dBA)	Average Post-Con (dBA)
A	Express Lane, west side, inside lane near E. Gwinn Place	92	92	92.3	92	92	92	92	91.8
B	Express Lane, east side, inside lane between E. Gwinn Place and E. Shelby Street	-	-	-	93	92	90	92	91.2
C	Express Lane, east side, inside lane between E. Gwinn Place and E. Allison Street	91	-	91.0	92	-	91	91	91.8
D	Express Lane, west side, south of Eastlake Avenue E.	-	-	-	-	-	92	92	91.7
1	Alley, 65’ off Allison St.	83	84	83.5	81	80	81	80	80.5
2	Brentwood Apts. 2923 Franklin, Right side of yard	82	82	82.4	79	79	78	79	78.8
3	Brentwood Apts. Drive way bet. 2923 and 2919 Franklin	82	82	82.4	80	80	80	81	80.3
4	Brentwood Apts. NW	74	73	74.3	71	72	71	72	71.5

		Pre-Construction			Post-Construction				
Location	Location Description	December 2009 (dBA)	February 2010 (dBA)	Average Pre-Con (dBA)	October 2010 (dBA)	February 2011 (dBA)	July 2011 (dBA)	September 2011 (dBA)	Average Post-Con (dBA)
	corner of House #2923 Franklin St								
5	NE Corner of Allison & East Lake	79	79	79.4	77	77	77	78	77.3
6	West of East Lake on North side Allison St. on the S. side of a building	70	69	70.3	69	69	69	70	69.3
7	On the park W side of I-5, (west of) next to a pine tree.	81	83	81.6	80	80	80	80	80.0
8	On the side walk West side of the walkway of Psychic Palm.	78	80	78.6	78	77	78	77	77.5
9	On the E side of East Lake Ave On a side walk, N edge of Lake Union Café	79	82	79.8	81	80	82	80	80.8
10	NW Harvard and Allison St. 75' from Br.	82	84	82.6	82	82	82	82	82.0
11	W side of Harvard across the Pillar and across NW. corner of house # 3109	79	82	79.8	82	82	82	82	82.0
12	N side of Franklin, where walk way starts for house #3109	77	80	77.8	79	79	77	77	78.0
13	NW Corner of Allison & Harvard, by the stop sign 150' E of I-5	79	79	79.4	78	78	79	78	78.3
14	NE side of Allison bet. Windows of House #	69	72	69.8	70	70	70	70	70.0

		Pre-Construction			Post-Construction				
Location	Location Description	December 2009 (dBA)	February 2010 (dBA)	Average Pre-Con (dBA)	October 2010 (dBA)	February 2011 (dBA)	July 2011 (dBA)	September 2011 (dBA)	Average Post-Con (dBA)
	810. 300’ E of I-5								
15	On the Alley, edge of Parking #103	79	77	79.3	77	76	77	75	76.3
16	S. Side of Gwinn, 30 ‘ E of Stop Sign	75	72	75.2	75	72	74	74	73.8
17	W side of Harvard St. Direct Traffic, between Shelby and Gwinn	83	80	83.2	82	83	82	82	82.3
18	W Side of Harvard St, on edge curve on Planting Strip.	83	82	83.3	82	83	82	83	82.5

Note: Missing values in table due to malfunctioning equipment, unable to collect data.

Table 5: Single factor ANOVA statistical tests comparing quarterly measurements for pre- and post-construction at grade measurements for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction						
SUMMARY						
Groups	Count	Sum	Average	Variance		
December 2009	18	1414	78.55555556	17.79084967		
February 2010	18	1422	79	20.70588235		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F critical
Between Groups	1.777777778	1	1.777777778	0.092359932	0.763050329*	4.130017699
Within Groups	654.4444444	34	19.24836601			
Total	656.2222222	35				
* - Not Statistically Significant						

ANOVA: Single Factor Post-Construction						
SUMMARY						
Groups	Count	Sum	Average	Variance		
October 2010	18	1403	77.94444444	17.46732026		
February 2011	18	1399	77.72222222	18.91830065		
July 2011	18	1400	77.77777778	18.30065359		
September 2011	18	1401	77.83333333	16.14705882		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F critical
Between Groups	0.486111111	3	0.162037037	0.009150327	0.998787537*	2.739502326
Within Groups	1204.166667	68	17.70833333			
Total	1204.652778	71				

- ** - Not Statistically Significant*

Table 5 shows the results of a statistical comparison of the two quarters of pre-construction measurements in the upper part of the table and a comparison of the four quarters of the first year of post-construction measurements. The results indicate that the preconstruction measurements are not significantly different from one another and thus there is no difference between the two quarters of data collected and the data they can be combined as an average. The lower half of the table indicates that the four quarters of data collected post-construction are not significantly different from one another and so there is no difference between the four quarters of data and there are no apparent seasonal differences thus the data can be combined as an average. Table 6 below shows the results of a single factor ANOVA statistical test which compares the average pre-construction versus the average post-construction at-grade measurements. The results indicate that the post-construction measurements are not statistically significantly different ($p>0.05$) from the pre-construction noise measurements. Most of the variation in the measurements can be explained by the differences between the different measurement locations.

Table 6: Single factor ANOVA statistical tests comparing averages for pre- and post-construction at grade measurements for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction vs. Post-Construction

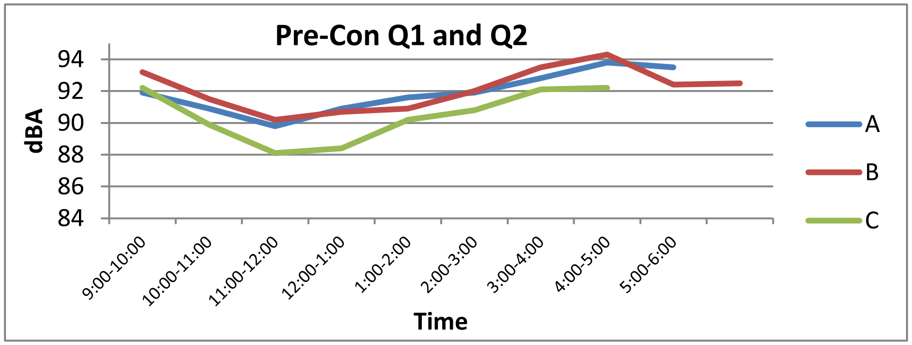
SUMMARY				
Groups	Count	Sum	Average	Variance
Pre-con (avg)	18	1420.096	78.89420401	18.06680845
Post-con (avg)	18	1401.444	77.85802258	17.27788507

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F critical
Between Groups	9.663048	1	9.663047616	0.546789158	0.464708*	4.130018
Within Groups	600.8598	34	17.67234676			
Total	610.5228	35				

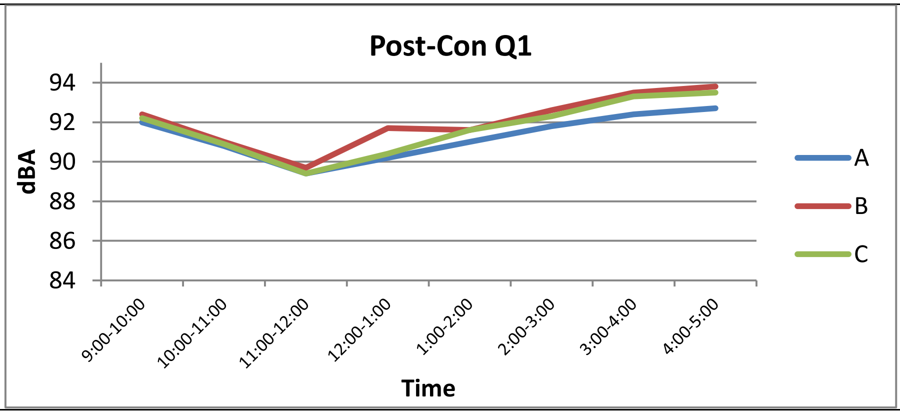
- * - *Not Statistically Significant*

Table 7: Plots of noise measurements collected on the bridge by quarter for pre- and post-construction for the Ship Canal Bridge pilot noise study.

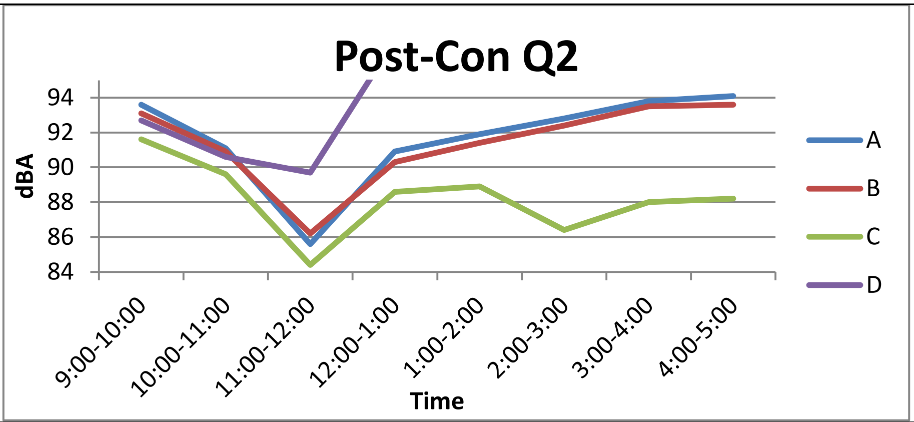
	Quarter 1 Leq (dBA)		Quarter 2 Leq (dBA)	
Time	B	C	A	D[1]
9:00-10:00	93.2	92.2	91.9	-
10:00-11:00	91.5	89.9	90.9	-
11:00-12:00[3]	90.2	88.1	89.8	-
12:00-1:00	90.7	88.4	90.9	-
1:00-2:00	90.9	90.2	91.6[2]	-
2:00-3:00	92	90.8	91.9	-
3:00-4:00	93.5	92.1	92.8	-
4:00-5:00	94.3	92.2	93.8	-
5:00-6:00	92.4		93.5	-



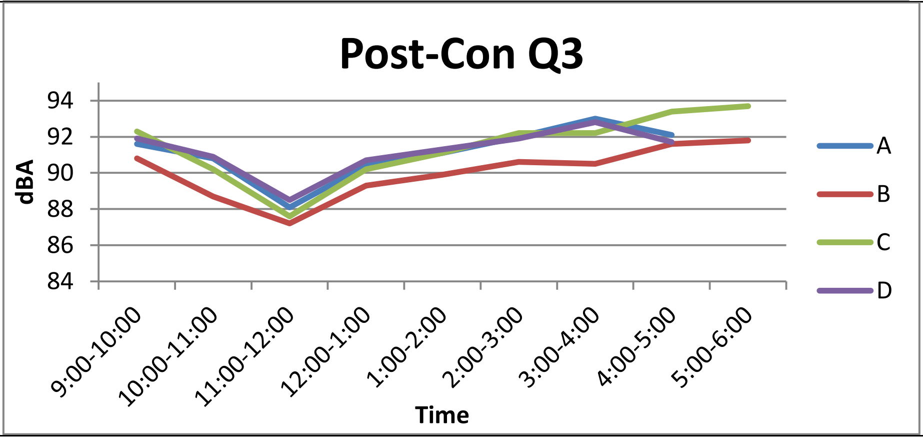
Time	A	B	C	D[1]
9:00-10:00	92	92.4	92.2	-
10:00-11:00	90.8	91	90.9	-
11:00-12:00[3]	89.4	89.7	89.4	-
12:00-1:00	90.2	91.7	90.4	-
1:00-2:00	91	91.6	91.6	-
2:00-3:00	91.8	92.6	92.3	-
3:00-4:00	92.4	93.5	93.3	-
4:00-5:00	92.7	93.8	93.5	-
5:00-6:00	-	-	-	-



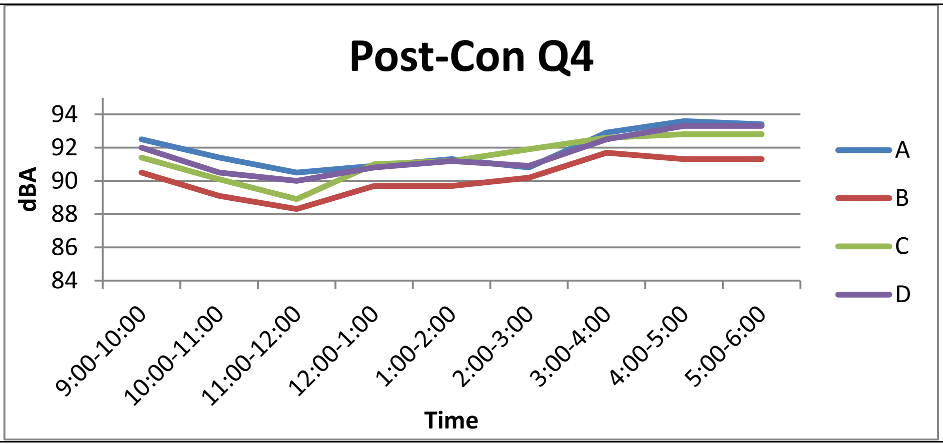
Time	A	B	C	D
9:00-10:00	93.6	93.1	91.6	92.7
10:00-11:00	91.1	90.9	89.6	90.6
11:00-12:00[3]	85.6	86.2	84.4	89.7
12:00-1:00	90.9	90.3	88.6	98.4
1:00-2:00	91.9	91.4	88.9	97.3
2:00-3:00	92.8	92.4	86.4[2]	96.3
3:00-4:00	93.8	93.5	88	96.5
4:00-5:00	94.1	93.6	88.2[2]	97.3
5:00-6:00	-	-	-	-



Time	A	B	C	D
9:00-10:00	91.6	90.8	92.3	91.9
10:00-11:00	90.8	88.7	90.2	90.9
11:00-12:00[3]	88.1	87.2	87.6	88.5
12:00-1:00	90.4	89.3	90.2	90.7
1:00-2:00	91.1	89.9	91.1	91.3
2:00-3:00	92	90.6	92.2	91.9
3:00-4:00	93	90.5	92.2	92.8
4:00-5:00	92.1	91.6	93.4	91.7
5:00-6:00	88.6[2]	91.8	93.7	87.8[2]



Time	A	B	C	D
9:00-10:00	92.5	90.5	91.4	92
10:00-11:00	91.4	89.1	90.1	90.5
11:00-12:00[3]	90.5	88.3	88.9	90
12:00-1:00	90.9	89.7	91	90.8
1:00-2:00	91.3	89.7	91.2	91.2
2:00-3:00	90.8	90.2	91.9	90.9
3:00-4:00	92.9	91.7	92.6	92.5
4:00-5:00	93.6	91.3	92.8	93.3
5:00-6:00	93.4	91.3	92.8	93.3



[1]-data not collected for this location
[2]-Statistical outlier (Dixon's Q-test), data excluded from analysis.
[3]-ship canal bridge closed to traffic during this period so data not used in analysis.

Site A

Table 7 shows the 15-minute Leq noise measurements collected each hour at the four locations on the bridge express lanes within the pilot study area. Some of the plots, for example post construction quarter 2, shows considerable variability in the plots when compared with the other sites on the bridge. Statistical analysis using Dixon's Q-test for outliers shows that some of the data are considered statistical outliers. At site C for quarter 2 post construction it appears that the meter may have lost internal power or some other internal malfunction that caused erroneous results after that point. The data for this meter at Site C was determined to be statistically significantly different than the other three quarters and the pre-construction measurements (Single Factor ANOVA, $p < 0.05$) and so this data was eliminated from subsequent analysis. Data identified as statistical outliers were also not included in subsequent analysis.

Table 8 provides the results of a single factor ANOVA comparing quarterly measurements at Site A on the bridge. The results of this comparison indicate that the quarterly measurements at Site A are not significantly different from one another ($p>0.05$). Table 9 compares the average pre-construction measurements at Site A versus the average post-construction measurements. The results show that they are not significantly different ($p>0.05$).

Table 8: Single factor ANOVA statistical tests comparing quarterly measurements for Site A on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction All Site A

SUMMARY						
Groups	Count	Sum	Average	Variance		
A-Q1	7	640.9	91.55714	0.832857		
A-Q2	7	648.2	92.6	1.726667		
A-Q3	7	641	91.57143	0.782381		
A-Q4	8	736.8	92.1	1.285714		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.216847	3	1.738949	1.49644	0.239772*	2.991241
Within Groups	29.05143	25	1.162057			
Total	34.26828	28				

- ** - Not Statistically Significant*

Table 9: Single factor ANOVA statistical tests comparing pre-construction versus average quarterly post-construction measurements for Site A on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction All Site D

SUMMARY						
Groups	Count	Sum	Average	Variance		
Pre-con A	8	730.676730	91.3345913	1.25227101		
Post-con A	8	732.251533	91.5314417	2.24958158		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.155000	1	0.155000	0.088524	0.770430*	4.600109
Within Groups	24.51296	14	1.750926			
Total	24.66796	15				

- ** - Not Statistically Significant*

Site B

Table 10 compares the four quarters at Site B and the results indicate that they are significantly different from one another ($p<0.05$). When plotted (Figure 5) it shows that the first and second quarter measurements are different from the third and fourth quarters.

Table 10: Single factor ANOVA statistical tests comparing quarterly measurements for Site B on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction All Site B

SUMMARY				
Groups	Count	Sum	Average	Variance
B-Q1	7	646.6	92.3714285	1.04904761
B-Q2	7	645.2	92.1714285	1.73904761
B-Q3	8	723.2	90.4	1.13714285
B-Q4	8	723.5	90.4375	0.85982142

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	25.774345	3	8.5914484	7.2744104	0.0010668	2.9751539
Within Groups	30.707321	26	1.1810508			
Total	56.481666	29				

- ** - Not Statistically Significant*

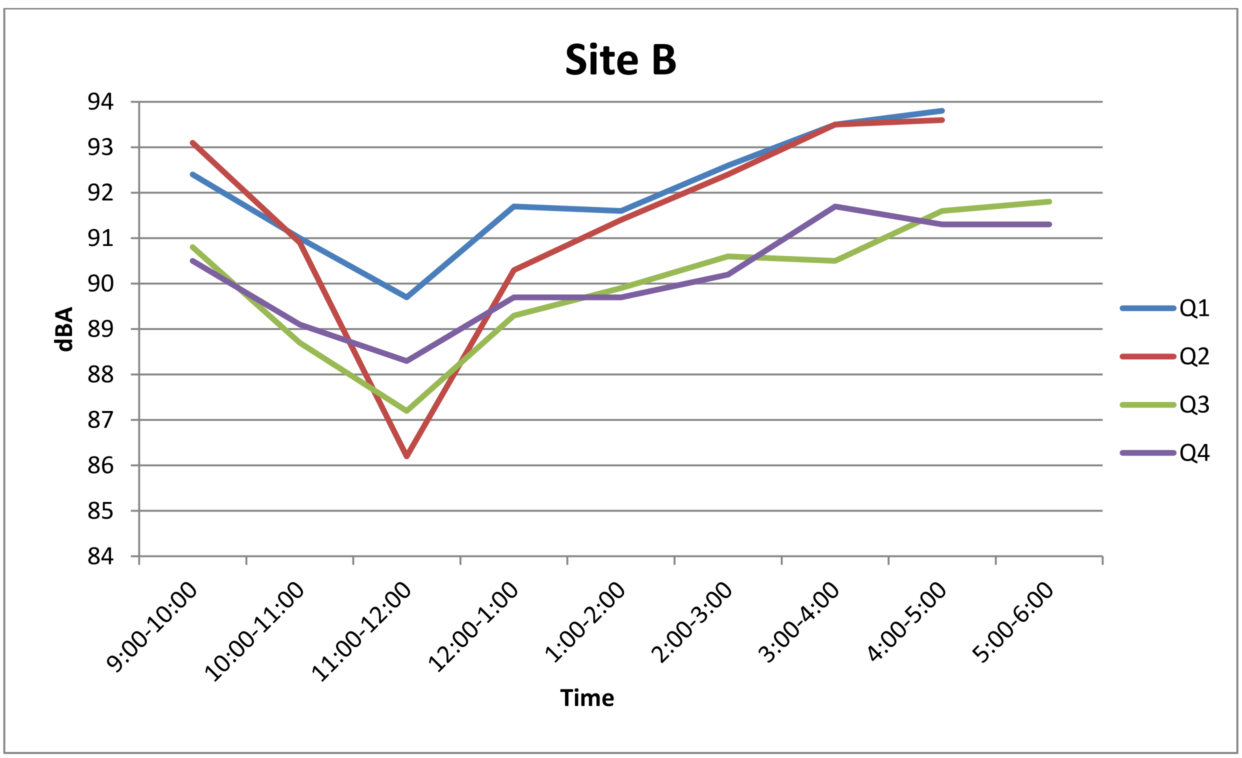


Figure 5: Site B quarterly measurements on the bridge for each quarter

Table 11 shows the results of a three separate single factor ANOVA tests comparing the four quarters in a pair wise manner to determine which are significantly different from one another. The results indicate that the first and second quarters are significantly different from the third and fourth quarters. Therefore, since the first and second quarters are not significantly different from one another they can be averaged. The same is true for the third and fourth quarter results.

Table 11: Single factor ANOVA statistical tests comparing post-construction quarterly measurements for Site B on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Post-Construction Site B						
SUMMARY						
Groups	Count	Sum	Average	Variance		
B-Q2	7	645.2	92.17143	1.739048		
B-Q3	8	723.2	90.4	1.137143		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.71505	1	11.71505	8.279507	0.012958	4.667193
Within Groups	18.39429	13	1.414945			
Total	30.10933	14				

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ANOVA: Single Factor Pre-Construction versus Post-Construction All Site D						
SUMMARY						
Groups	Count	Sum	Average	Variance		
B-Q1	8	736.3	92.0375	1.79125		
B-Q3	9	810.4	90.04444	2.132778		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	16.82373	1	16.82373	8.525261	0.010562	4.543077
Within Groups	29.60097	15	1.973398			
Total	46.42471	16				

•

ANOVA: Single Factor Post-Construction Site B						
SUMMARY						
Groups	Count	Sum	Average	Variance		
B-Q1	8	736.3	92.0375	1.79125		
B-Q4	9	811.8	90.2	1.26		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	14.30007	1	14.30007	9.483331	0.00763	4.543077
Within Groups	22.61875	15	1.507917			
Total	36.91882	16				

- ** - Not Statistically Significant*

Table 12 shows the first and second quarter averaged data compared against the averaged third and fourth quarter data using a single factor ANOVA. The results indicate that they are not significantly different (p>0.05) and so the two averages can be averaged together for further comparisons. Table 13 shows the results of a single factor ANOVA comparing the average pre-construction measurements against the averaged first and second and averaged third and fourth quarters at Site B. Results indicate that they are not significantly different from one another (p>0.05).

Table 12: Single factor ANOVA statistical tests comparing post-construction average quarter measurements for Site B on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction All Site B

SUMMARY

Groups	Count	Sum	Average	Variance
Post-con B 1+2	8	734.2674	91.78343	3.083408
Post-con B 3+4	9	811.2034	90.13371	1.582299

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.6943	2	5.847149	2.818299	0.080403*	3.422132
Within Groups	47.71829	23	2.074708			
Total	59.41259	25				

- ** - Not Statistically Significant*

Table 13: Single factor ANOVA statistical tests comparing pre-construction versus average quarterly post-construction measurements for Site B on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction All Site B

SUMMARY

Groups	Count	Sum	Average	Variance
Pre-con B	9	819.7094	91.07882	1.684505
Post-con B 1+2	8	734.2674	91.78343	3.083408
Post-con B 3+4	9	811.2034	90.13371	1.582299

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.6943	2	5.847149	2.818299	0.080403*	3.422132
Within Groups	47.71829	23	2.074708			
Total	59.41259	25				

- ** - Not Statistically Significant*

Site C

Table 14 shows the results of a single factor ANOVA comparing quarterly measurements at Site C on the bridge. The results of this comparison indicate that the quarterly measurements at Site C are significantly different from one another (p<0.05). When plotted (Figure 6) it shows that the second quarter measurements are quite different from the other three quarters. In fact it appears that the noise meter used during the second quarter measurements at this site may have had a loss of power or other internal malfunction causing the measurements to more or less level out after the noon measurement rather than gradually increasing as with the other quarters. Additionally two of the measurements collected at 2:00 pm and 4:00 pm were tested and found to be statistical outliers (Dixon's Q-test). Therefore, the second quarter results were eliminated from further analysis.

Table 14: Single factor ANOVA statistical tests comparing quarterly measurements for Site C on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction All Site C

SUMMARY

Groups	Count	Sum	Average	Variance
C-Q1	7	644.2	92.0285714	1.3323809
C-Q2	5	446.7	89.34	1.928
C-Q3	8	735.3	91.9125	1.7498214
C-Q4	8	733.8	91.725	0.9507142

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	26.907107	3	8.9690357	6.2194924	0.0028073	3.0087865
Within Groups	34.610035	24	1.4420848			
Total	61.517142	27				

- ** - Not Statistically Significant*

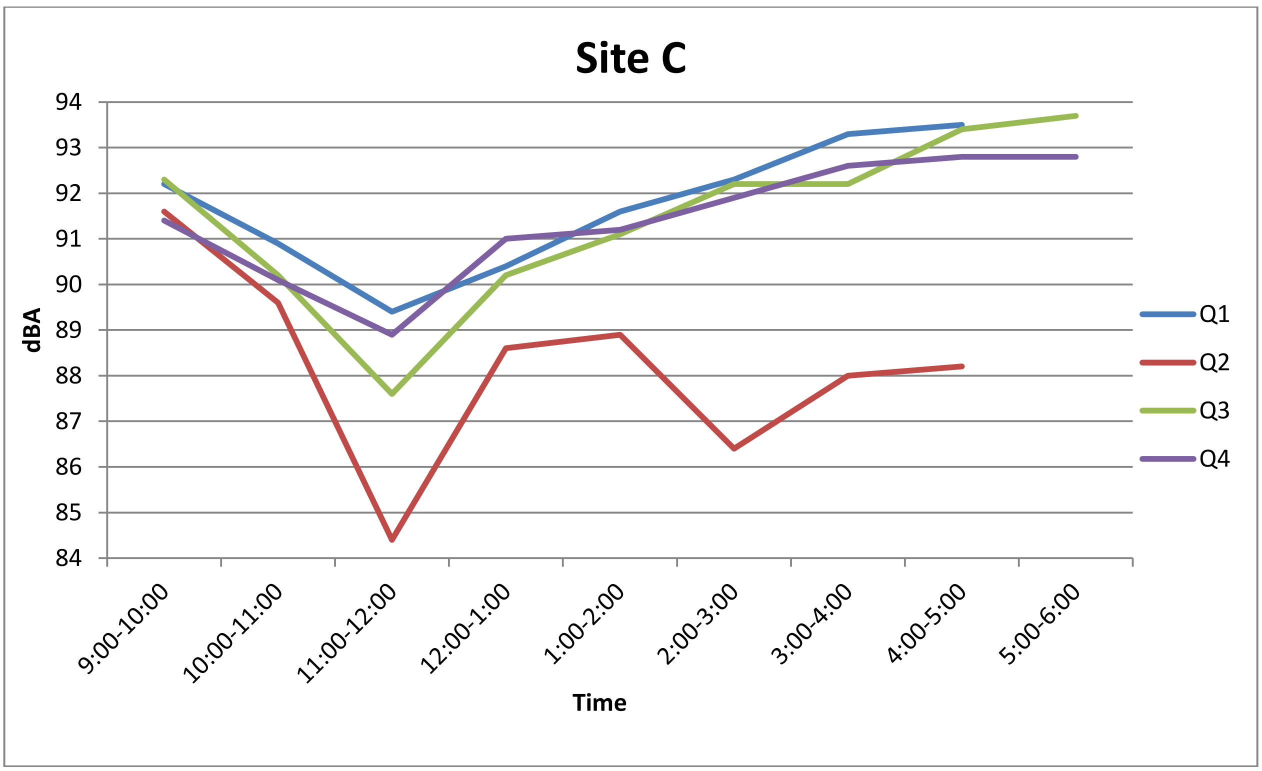

Figure 6: Site C quarterly measurements on the bridge for each quarter

Table 15 shows the results of a single factor ANOVA test comparing the first, third and fourth quarters with the anomalous second quarter removed from the analysis. The results indicate that these three quarters are not significantly different ($p>0.05$) from one another and so can be combined as an average for further analysis. Table 16 shows the results of comparing the average pre-construction measurements versus the average three quarters of the post-construction measurements. The results of the single factor ANOVA show that they are not significantly different from one another ($p<0.05$).

Table 15: Single factor ANOVA statistical tests comparing three quarterly measurements for Site C on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction Three Quarters Site C						
SUMMARY						
Groups	Count	Sum	Average	Variance		
C-Q1	7	644.2	92.02857	1.332381		
C-Q3	8	735.3	91.9125	1.749821		
C-Q4	8	733.8	91.725	0.950714		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.355008	2	0.177504	0.131983	0.877113*	3.492828
Within Groups	26.89804	20	1.344902			
Total	27.25304	22				

- ** - Not Statistically Significant*

Table 16: Single factor ANOVA statistical tests comparing pre-construction versus average quarterly post-construction measurements for Site A on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction All Site D						
SUMMARY						
Groups	Count	Sum	Average	Variance		
Pre-con C	8	730.6767	91.33459	1.252271		
Post-con C	8	733.8692	91.73365	0.981175		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.636984	1	0.636984	0.570405	0.462616*	4.60011
Within Groups	15.63412	14	1.116723			
Total	16.27111	15				

- ** - Not Statistically Significant*

Site D

When the quarterly measurement data from Site D is evaluated an outlier test (Dixon's Q-test) shows that most of the data collected during the second quarter are considered statistical outliers. Therefore, the second quarter data used in the analysis below is limited. A single factor ANOVA for Site D (Table 17) shows that they are not significantly different from one another ($p>0.05$). Table 18 shows a comparison of the Site D average pre-construction measurements versus the average post construction measurements. The results show that they are not significantly different from one another ($p>0.05$).

Table 17: Single factor ANOVA statistical tests comparing quarterly measurements for Site D on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction All Site D

SUMMARY						
Groups	Count	Sum	Average	Variance		
D-Q2	3	280.6	93.533333	11.743333		
D-Q3	7	641.2	91.6	0.5033333		
D-Q4	7	641.2	91.6	1.06		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	9.234509	2	4.6172549	1.9667820	0.1766973*	3.7388918
Within Groups	32.86666	14	2.3476190			
Total	42.101176	16				

- ** - Not Statistically Significant*

Table 18: Single factor ANOVA statistical tests comparing pre-construction versus average quarterly post-construction measurements for Site D on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction All Site D

SUMMARY						
Groups	Count	Sum	Average	Variance		
Pre-con D	8	730.6767	91.33459	1.252271		
Post-con D	7	636.6882	90.95546	3.976341		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.536637	1	0.536637	0.213839	0.651419*	4.667193
Within Groups	32.62394	13	2.509534			
Total	33.16058	14				

- ** - Not Statistically Significant*

Table 19 compares the average pre-construction noise measurements against the average post construction measurements at each site. The results indicate that they are not significantly different from one another ($p>0.05$).

Table 19: Single factor ANOVA statistical tests comparing quarterly measurements for Site D on the bridge for the Ship Canal Bridge pilot noise study.

ANOVA: Single Factor Pre-Construction versus Post-Construction All Site D

SUMMARY				
Groups	Count	Sum	Average	Variance
Pre-Con	8	730.67673	91.334591	1.2522710
Post-Con A	8	732.25153	91.531441	2.2495815
Post-Con B	8	728.29005	91.036257	1.9414925
Post-Con C	8	733.86918	91.733647	0.9811752

Post-Con D	7	643.73185	91.961693	2.0544550		

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.873490	4	0.9683727	0.5746179	0.6829113*	2.6498940
Within Groups	57.298373	34	1.6852462			
Total	61.171864	38				

- ** - Not Statistically Significant*

Figure 7 shows the measured sound level only at the 500 Hertz (Hz) frequency and compares the pre-construction sound levels at each site against the post-construction sound levels. The absorptive test panel was tested under laboratory conditions to absorb 74% of the sound energy at 500 Hz and 72% at 800 Hz. Figure 7 shows that the measured absorption at 500 Hz in the field, under much less controlled conditions, which ranges between 0% (Sites 11 and 17, which are outside of the test area), and 54% at Site 1. The overall average is 22% absorption at 500 Hz. There is considerable variability at each site within the post-construction measurements as well as between sites. This is primarily due to the other traffic sound sources in the measurement area influencing the sound levels at this frequency.

Figure 8 shows the measured sound level only at the 800 Hz frequency and compares the pre-construction sound levels at each site against the post-construction sound levels. The percent absorption measured in the field under uncontrolled conditions ranges between 0% (Sites 11 and 17 which are outside the test area) to 57% at Site 1. The overall average absorption at 800 Hz is 27%.

Based on these results it appears that the panels are able to remove some percentage of the noise at these frequencies, however competing sources from the mainline, direct path express lanes, Harvard and Eastlake Avenues reduce the ability to accurately measure how much noise they are able to remove from the local environment. There could also be reflection/diffraction of noise off and around the edges of the panels.

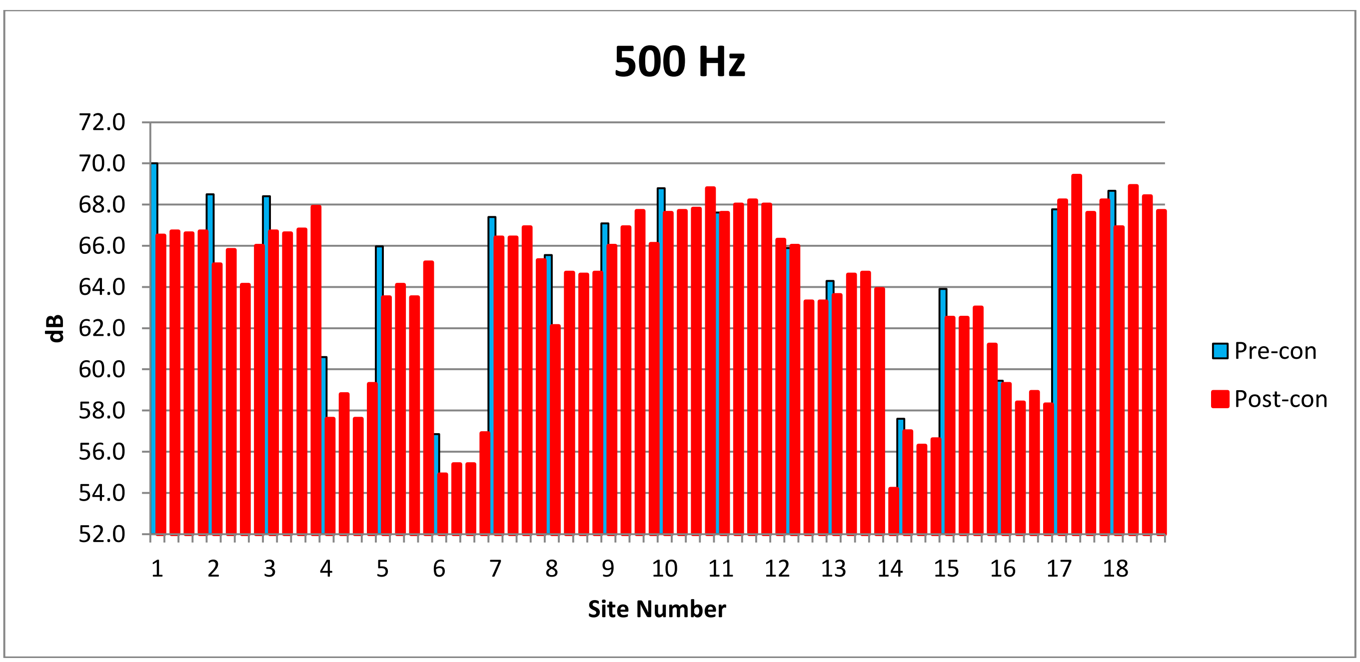

Figure 7: Comparison of noise levels at the 500 Hertz (Hz) frequency for pre- and post-construction measurements at all sites.

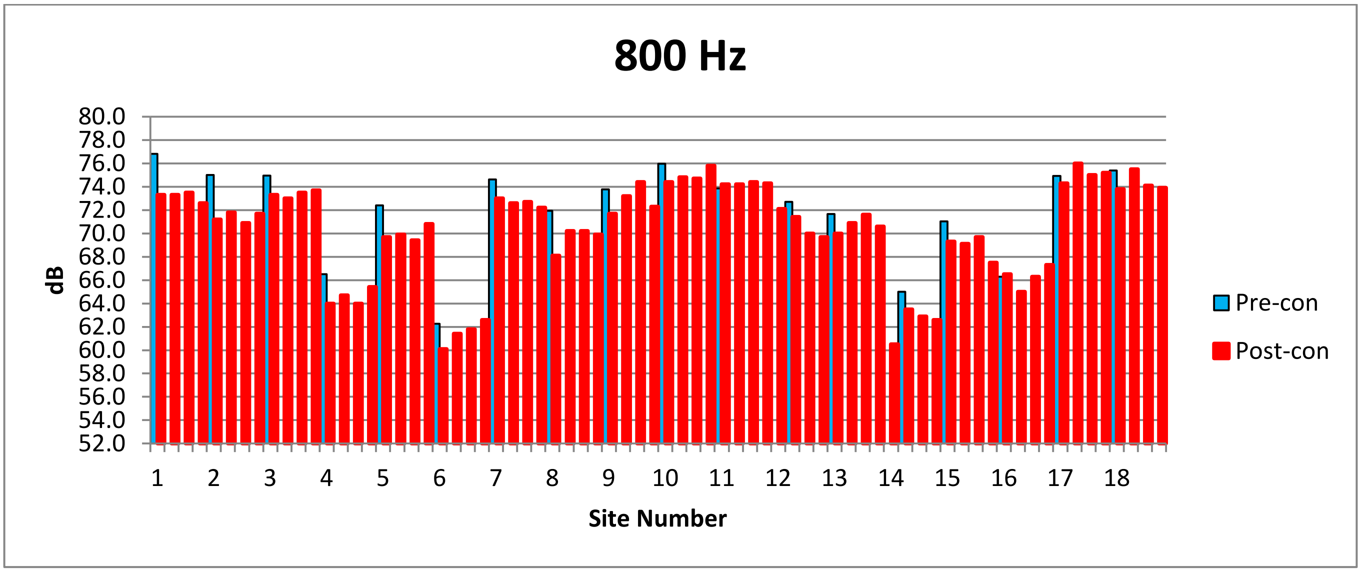

Figure 8: Comparison of noise levels at the 800 Hertz (Hz) frequency for pre- and post-construction measurements at all sites.